The Changing Nature of Atmospheric Rivers

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(Manuscript received 26 April 2024, in final form 6 December 2024, accepted 28 December 2024)

ABSTRACT: Atmospheric rivers (ARs) are expected to strengthen in a warming climate, largely due to the thermodynamic (moistening) effect. Here, we show that this trend is already evident in historical reanalysis data using the AR Tracking Method Intercomparison Project (ARTMIP) tier 2 AR detection tools (ARDTs) and variants of our own global AR detection applied to ERA5, MERRA-2, and JRA-55 reanalysis data. Over the 1980–2019 (ARTMIP) and 1980–2023 (variants) periods, total AR area increased by 6%–9%. AR integrated water vapor (IWV) increased by 1.5%–2.5% while integrated vapor transport (IVT) increased by less than 1% and 850-hPa wind speed ($|\mathbf{V}_{850}|$) and vertically integrated moisture flux convergence (VIMFC) both decreased. IWV increases were the most robust overall. All trend magnitudes were sensitive to subsetting, with fixed-frequency subsets consisting of the most intense AR grid points showing larger increases of 3%–4% IVT, 4%–6% IWV, and 6%–10% VIMFC, this last opposing a decreasing AR-mean VIMFC trend likely associated with large area increases. For individual ARs, maximum IVT and IWV increased at ~3–6× and ~1.5–2× the rate of AR-mean values, respectively. Regional changes were often even larger, particularly for extreme events, though most geospatial trends had low detectability under a false discovery rate control framework. Ultimately, despite considerable ARDT and methodological diversity, we found robust consensus moistening and expansion of ARs between 1980 and 2023. However, further research is required to determine the extent to which these trends are affected by reanalysis observational assimilation changes. For example, previous studies indicate that certain reanalyses misrepresent 1980–94 atmospheric moistening and so may underestimate historical AR expansion and intensification rates.

SIGNIFICANCE STATEMENT: Atmospheric rivers (ARs) are narrow, elongated regions of intense atmospheric moisture transport that are responsible for a large proportion of midlatitude extreme precipitation. Projections show that ARs will intensify due to warmer air's ability to hold more moisture. We find that ARs have already become more frequent, larger, and moister during the 1980–2023 time frame. Extreme AR conditions have intensified at a faster rate than the mean, and certain measures of intensity have decreased overall but still account for larger areas of extreme conditions due to AR area increases. Our results expand existing evidence for global AR intensification and identify important caveats for consideration in future work.

KEYWORDS: Atmospheric river; Fluxes; Extreme events; Climate variability; Trends

1. Introduction

Since its original definition in the 1990s (Newell et al. 1992; Newell and Zhu 1994; Zhu and Newell 1998), the concept of the atmospheric river (AR) has increasingly entered the public consciousness, driven largely by the severe storms that the "rivers in the sky" bring to the west coasts of the Americas and Europe. Now, in the mid-2020s, ARs grace the front pages of major news sites and even have their own rating system (categories 1–5, like hurricanes; see Ralph et al. 2019). They have been linked to the polar jet, tracked across ocean basins, sorted into moisture- and wind-dominant and dusty varieties, and even described hundreds of years before direct detection was possible using tree-ring and precipitation data (Gonzales et al. 2020; Voss et al. 2021; Zhou et al. 2021; Maclennan et al. 2022; Zhou et al. 2022; Borkotoky et al. 2023; Simon et al. 2024).

Globally, ARs are particularly impactful because, depending on the AR definition, they produce the majority of midlatitude extreme precipitation (see Arabzadeh et al. 2020). Changes in AR characteristics will thus contribute significantly to overall changes in the water cycle, from drought risk to dangerous flooding. Global warming–induced change is hardly unique to ARs—subdaily and convective precipitation extremes may increase even more rapidly than stratiform precipitation (Morrison et al. 2019; Martel et al. 2020; Chinita et al. 2021). But because of the sheer amount of extreme precipitation produced by ARs, changes in their characteristics will be crucial in determining changes in the overall extreme precipitation profile across the extratropics. In addition, certain recent studies have shown disproportionate historical increases in AR-type extreme precipitation (Lochbihler et al. 2017; Hatsuzuka et al. 2021).

To first order, the expected AR response to climate change is one of moistening. As dictated by the Clausius–Clapeyron

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Supplemental information related to this paper is available at the Journals Online website: https://doi.org/10.1175/JCLI-D-24-0234.s1.

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DOI: 10.1175/JCLI-D-24-0234.1